Problems of Internal Constitution and Kinematics of Main Sequence Stars

Bengt Strömgren

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The particular property of the distribution of stars in the Hertzsprung-Russell diagram which we refer to when we speak of main sequence stars has been known now for more than fifty years. Through the theoretical work of Eddington, Russell and Vogt it became clear that the main sequence stars are stars in secular equilibrium, i.e. stars for which there is a balance between energy generation and radiation into space.

The development of Bethe and v. Weizsäcker of the theory of energy generation through transmutation of hydrogen into helium made possible an analysis of stellar evolution through the main sequence phase, but it was only after it was realized that mixing of material in stellar interiors is essentially limited to regions in convective equilibrium that significant progress was made. Chandrasekhar and collaborators tackled the problem soon after the development of Bethe's theory, and - following a lead by Eddington - Öpik, M. Schwarzschild, Sweet and Mestel investigated the question of mixing in stellar interiors. The work of Tayler, Kushwaha, Henyey, Le Levier and Levee, Haselgrove and Hoyle, and others, regarding stellar evolution during the hydrogen-burning phase followed, and new insights into the problems of internal constitution of main sequence stars were thereby gained.

In today's lecture I should like to discuss the following questions:

1. Can we distinguish observationally between stars of different ages in the main sequence band. and

2. Can we account for the main sequence band in terms of evolution during the hydrogen-burning phase. In particular, can we account for the location of the so-called zero-age line, as well as for the observed width of the main sequence band, and can we determine reliable ages for main sequence stars.

3. Is it possible at the present stage of development of observation and theory to combine ages and space velocities of main sequence stars to obtain significant knowledge regarding their places of formation in the galaxy;

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and if so, what is the general nature of the results arrived at.

The first question is essentially a question of observational astronomy. Work carried out during the last decades by a number of astronomers has shown that we can indeed distinguish observationally between stars of different ages in the main sequence band.

The situation is clearest for stars that belong to galactic clusters. Here extensive photometric work by a number of observers has led to an empirical qualitative age-classification of main sequence stars (cf. e.g. A. Sandage(1)).

In the case of field stars, where we do not posses the special advantages of investigation characteristic of the case of stars that are members of galactic clusters, it has nevertheless proved possible to segregate stars in the main sequence band according to age, namely through two-dimensional spectral classification. The MK system of classification developed by W. W. Morgan and P. C. Keenan (cf. H. L. Johnson and W. W. Morgan (2)) makes possible a division of main sequence stars of the same spectral class according to luminosity. For B and A stars the main sequence band is divided into three portions corresponding to luminosity classes III, IV and V; and for F and early G stars into two, of luminosity classes IV and V.

Each compartment of the two-dimensional MK classification system contains stars that are fairly homogeneous with regard to age. For some purposes of investigation the accuracy of the classification according to age which is thus obtained is adequate, but higher precision is nevertheless desirable. In recent years various attempts have been made at achieving more accurate spectral classification through quantitative methods based on photometry, photographic or photoelectric, of suitably selected wavelength regions. In a general way the procedure in question can be regarded as further developments of methods devised by Lindblad, and Öhman, over thirty years ago. The work of Barbier and Chalonge and of Chalonge and collaborators (cf. D. Barbier (3) and D. Chalonge (4)), that of R. Petrie (5), R. F. Griffin and R. O. Redman (6), T. J. Deeming (7), and T. and J. H. Walraven (8) is well known (for a recent survey of methods of quantitative spectral classification cf. e.g. B. Strömgren (9)).

Here I should like to discuss two methods of spectral classification based on photoelectric photometry. The first utilizes two indices l and c measuring the strength of the Hβ line and the Balmer discontinuity, respectively, and is applicable to B, A and F stars (B. Strömgren (10) and (11)). A similar method for two-dimensional classification of B stars, based on Hβ photometry

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and UBV photometry, has been developed by D. Crawford (12). The intrinsic color $(U-B)_o$ is derived from $(U-B)$ and $(B-V)$ in standard fashion and then combined with an index β measuring the Hβ strength to yield two-dimensional classification. (The index β is similar to 1, but somewhat more sensitive to the changes in Hβ strength because a more suitable interference filter for the isolation of the Hβ band is used). Since the 1c- and β-$(U-B)_o$- methods have been described previously I shall restrict myself here to comments on their use for determination of ages of main sequence B stars.

In a β-$(U-B)_o$ diagram the B stars of luminosity classes III-V populate a band with a well defined limiting envelope toward high β-values, the zero-age line. For given $(U-B)_o$ the value of β decreases with increasing luminosity. The width of the main sequence band in β is a little more than $0^m_.1$ for late B stars and somewhat less for the early ones. The properties of the distribution in the 1c- diagram are similar. Since β is determined by photoelectric photometry to an accuracy of better than $0^m_.01$ it appears quite feasible to distinguish observationally between B stars of different ages within the main sequence band. Indeed, if the stars in question can be satisfactorily described in terms of two-dimensional classification, then age determination to an accuracy of one-tenth of the main sequence lifetime, or better, should be possible. However, the question arises whether parameters beyond the two basic stellar parameters, mass and age, influence the properties of the star in question to a degree that would make ages determined from observed values of 1 and c, or β and $(U-B)_o$, considerably less accurate (cf. D. Chalonge (13), B. Strömgren (14), T. and J. H. Walraven (15), and R. Hardie and D. Crawford (16)).

In the investigations just referred to (particularly (15) and (16)) the question is examined through comparison of absolute magnitudes determined from the two-dimensional classification with values obtained on the assumption of association membership. The occurrence of undetected spectroscopic binaries as well as the possible inclusion of non-members in the material complicates the discussion. However, the conclusion is reached that an influence of stellar parameters beyond mass and age is present, and that the accuracy of the absolute magnitudes derived from two-dimensional classification is somewhat less than what would be the case if the limit given by the probable errors of the photometry were reached. The actual probable errors of the M_v- values appear to be about $\pm~0^m_.2$, rather than $\pm~0^m_.1$.

In associations where the main sequence band extends to O-B2 stars the less luminous late B type stars are expected to populate a narrow band close to the zero-age line in the 1c- diagram or β-$(U-B)_o$ diagram. In the cases

where the test has been applied, this was in fact the case. A further test of the reliability of ages determined by these methods can be made in the following way.

On the basis of photoelectric UBV and $H\beta$ photometry by D. Crawford (17) for 501 B8 and B9 stars brighter than 6.5^m absolute magnitudes and distances have been computed, as well as space velocities for all those stars for which radial velocities are available. The space velocity component $|W|$ at right angles to the galactic plane is generally small for these stars, as expected, averaging about 6 km/sec. However eight stars have $|W|$ - values greater than 13 km/sec (the average being 18 km/sec) and therefore in the oscillations at right angles to the galactic plane spend most of their lifetime outside the regions where star formation occurs. We conclude that they were formed either very recently, less than 5-10 million years ago, or that their age is about equal to one-half the period of oscillation. In view of the location of these stars in the H-R diagram the latter is unlikely, and we should therefore expect to find them very close to the zero-age line in the $\beta - (U-B)_o$ diagram. In fact, this is the case for all of them, the average deviation in β being only 0.13 times the width of the main sequence band.

The conclusion reached is that the influence of parameters beyond mass and age notwithstanding methods such as the 1c-method or the $\beta - (U-B)_o$-method do make it possible to distinguish observationally between stars of different ages in the main sequence band, and that they yield ages for B stars with probable errors equal to perhaps 10 - 15 per cent of the main sequence band lifetime in question.

The second type of classification method based on photoelectric photometry that I should like to discuss utilizes three indices derived from four-color photometry in bands of intermediate width. The bands in question are the following:

	Central Wavelength	Halfwidth
u	3500Å	300Å
v	4110	190
b	4670	180
y	5470	230

The u band is isolated with the help of a combination of Schott glass filters, the other three through Schott interference filters. The photoelectric photometry was carried out making consecutive measures through the four filters.

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The u band is located below the effective wavelength of the Balmer discontinuity. For the F and G stars the v band intensity is strongly affected by absorption lines while the b and y intensities are considerably less, and about equally reduced by the line effect.

Three indices were derived from the magnitudes u, v, b and y, namely,

$b - y$ a color index that is relatively insensitive to chemical-composition effects

$c_1 = (u-v)-(v-b)$ a color difference that is a measure of the Balmer discontinuity

$m_1 = (v-b)-(b-y)$ a color difference that is a measure of the total intensity of the metal lines in the v-band.

The uvby method has been applied to stars in the spectral range A2-G2. Photoelectric photometry was obtained for 1217 stars brighter than visual magnitude $6^m.5$ and nearly all between declinations $-10°$ and $+65°$. In addition a number of fainter stars that are members of the Hyades, Pleiades and Coma clusters were also observed. The observations were made by C. Perry and myself with the 20-inch reflector of Mount Palomar Observatory, and the 36-inch and 16-inch reflectors of Kitt Peak National Observatory. The accuracy of the indices b-y, m_1 and c_1 was as follows,

$\pm 0^m.004$ p.e. of catalogue value of b-y

± 0.005 p.e. of catalogue value of m_1

± 0.006 p.e. of catalogue value of c_1

(2 observations, each consisting of two sets of filter measures)

The aim of the observations was the determination of color index, absolute magnitude, and a chemical-composition index. The relation of the uvby method used for this purpose to the six-color method of J. Stebbins and A. Whitford, the methods of photographic photometry developed by W. Becker, and the spectrophotometric methods of D. Chalonge and collaborators is discussed in (9).

It was expected that the combination of the indices b-y and c_1 would give the visual absolute magnitude, in other words that the location of a star in a $c_1-(b-y)$ diagram would determine its place in the Hertzsprung-Russell diagram. This turned out to be the case. Fig. 1 shows the distribution of the A2 - G2 stars in question in the $c_1-(b-y)$ diagram. (The plotted points correspond to a preliminary version of the photometric catalogue just referred to, as does the following discussion; the changes

in question are small and of no consequence). The distribution is seen to have a well defined lower envelope. This represents the zero-age line of practically unevolved main sequence stars. For a given b-y the luminosity increases with increasing c_1. There is a fairly well defined upper limit to the main sequence band. The points above this limit correspond to giant and supergiant stars of luminosity classes II and I for the A stars, III, II and I for the F and G stars.

A calibration of the c_1-(b-y) diagram in terms of visual absolute magnitude M_v has been carried out on the basis of M_v-values for 130 A2 - G2 stars with relatively accurate cluster parallaxes or trigonometric parallaxes. The results of the calibration are summarized in the following table.

b-y	c_1 zero-age line	M_v zero-age line	Factor	$\dfrac{\Delta M_v}{\Delta c_1}$	Sp. Class
$0\overset{m}{.}00$	$1\overset{m}{.}00$	$1\overset{m}{.}5$	9		A0
0.05	0.96	2.0	8		A3
0.10	0.88	2.4	8		A6
0.15	0.78	2.7	8		A8
0.20	0.65	3.1	8		F0
0.25	0.52	3.5	9		F2
0.30	0.42	3.9	10		F5
0.35	0.35	4.5	13		F8
0.40	0.31	5.0	16		G2

The two first columns give c_1 as function of b-y for the zero-age line while the third column contains the absolute visual magnitude M_v, also for the zero-age line. If we define Δc_1 as the measured c_1-value minus the zero-age c_1-value corresponding to the measured (b-y)-value. then

$$M_v = M_v \text{ (zero-age line) } - \Delta c_1 \cdot \frac{\Delta M_1}{\Delta c_1}$$

where the factor to Δc_1 is given in the fourth column of the calibration table.

Combining the known values of the probable errors of the photoelectric photometry with the information given by this calibration we derive that the photometric errors lead to a p.e. of the M_v of $\pm 0\overset{m}{.}1$ to $\pm 0\overset{m}{.}2$. according to the spectral class. The residuals M_v(observed) minus M_v (photometric) for the calibration stars indicate that the actual p.e. is only slightly larger than

the lower limit corresponding to the photometric p.e.

As an example the following table gives the absolute visual magnitude M_v according to van Bueren (18) for twenty-six bright members of the Hyades cluster as well as M_v determined from measured values of the indices (b-y) and c_1, and the corresponding residuals. The components U, V and W of the space motion (uncorrected for solar motion, new galactic coordinate system) as computed from distances corresponding to the photometrically determined M_v-values are also given for the sake of illustration.

Star	M_v phot.	M_v v. Bueren	Res.	U	V	W	
HR1201	$3.^m2$	$3.^m1$	$-0.^m1$	-40	-16	-3	
45 Tau	3.2	3.2	0.0	-39	-17	-3	
51 Tau	2.3	2.3	0.0	-39	-16	-2	
57 Tau	2.5	2.7	+0.2	-44	-18	-4	
58 Tau	2.2	2.1	-0.1	-39	-17	-2	
63 Tau	2.7	2.5	-0.2	-37	-16	-2	Met. 1. st.
64 Tau	1.6	1.9	+0.3	-40	-20	-2	
65 Tau	1.1	1.0	-0.1	-43	-18	-4	
67 Tau	2.2	2.3	+0.1	-36	-21	-1	
HR1403	2.6	2.6	0.0	-39	-16	2	Met. 1. st.
76 Tau	2.7	3.0	+0.3	-46	-20	-3	
78 Tau	1.2	1.0	-0.2	-40	-13	-6	
79 Tau	2.0	2.0	0.0	-36	-17	+1	
HR1427	1.7	1.8	+0.1	-40	-18	-1	
81 Tau	2.6	2.4	-0.2	-41	-16	-3	
83 Tau	2.4	2.4	0.0	-40	-18	-2	
85 Tau	2.9	3.0	+0.1	-38	-18	-1	
89 Tau	2.5	2.7	+0.2	-40	-18	-1	
90 Tau	1.1	1.3	+0.2	-46	-18	-3	
92 Tau	1.4	1.4	0.0	-38	-16	-1	
HR1480	2.3	2.3	0.0	-38	-17	-1	
HR1507	2.4	2.5	+0.2	-40	-18	-2	
97 Tau	1.8	2.0	+0.2	-39	-18	-2	
102 Tau	1.2	1.3	+0.1	-42	-16	-4	
HR1670 br.	2.5	2.7	+0.2	-42	-20	-3	Met. 1. st.
16 Ori	2.3	2.1	-0.2	-36	-15	-1	Met. 1. st.

Four of the listed stars are metallic line stars, and we note that the residuals for these stars do not differ significantly from the others.

Inspection of Fig. 1 shows that the main sequence band has a width in c_1 of about $0^m.2$ for A stars and somewhat less for the later types. In view of the precision obtained in the determination of b-y and c_1 we conclude that a separation according to age within the main sequence band is quite feasible. A similar conclusion is reached when the distribution in the Hertzsprung-Russell diagram as obtained with the help of the M_v-calibration is considered. In fact, age determinations of somewhat higher relative accuracy than for the B stars appear possible.

It should be emphasized that the c_1-(b-y)-method is sensitive to the influence of interstellar reddening, contrary to what is the case for the lc-method. However, the present program of investigation is limited to stars within about 100 parsec where the effect is very small. In comparison with the lc-method the c_1-(b-y)-method has the advantage that it is applicable for stars later than F7, at least up to spectral class G2.

The c_1-(b-y) diagram in Fig. 1 contains several high-luminosity stars above the main sequence band. Some of them are appreciably reddened, and the method of classification does not apply to them. However, they are segregated from the main sequence stars without difficulty.

Three indices, namely, b-y, m_1 and c_1 were derived from the photoelectric uvby photometry. We shall now discuss the problem of chemical-composition differences within the sample of stars considered on the basis of this material. We shall return to the question of the calibration of the c_1-(b-y) diagram in terms of M_v to see which corrections if any, must be applied to allow for such differences in chemical composition as might be indicated by the material of m_1 - indices.

Fig. 2 shows the distribution in an m_1-(b-y) diagram of the stars of the main sequence band ($\Delta c_1 < 0^m.15$). For the late F and early G stars (b-y $0^m.30 - 0^m.40$) the range of variation of m_1 for a given b-y is considerable, much larger than the photometric p.e. of m_1. An examination of the correlation of m_1 with Δc_1 as just defined shows that the variation of m_1 is not explicable in terms Δc_1, or absolute magnitude variation within the main sequence band. In other words, the uvby photometry shows that the spectral properties are significantly influenced by a parameter beyond the basic parameters mass and age. A similar conclusion was suggested by discussions of the (U-B)-(B-V) diagram of main sequence stars (cf. H. L. Johnson and W. W. Morgan (2) and

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H. L. Johnson and C. F. Knuckles (19)), and more clearly by the spectrophoto-
metric work of Chalonge and collaborators (D. Chalonge (3)) as well as by a
discussion based on photoelectric observations of a metal index m similar to
the index m_1 (B. Strömgren (20)).

Results of spectrophotometric observations made at high dispersion
of total equivalent widths of absorption lines for different portions of the
spectrum (cf. W. G. Melbourne (21) and M. Schwarzschild, L. Searle and R. Howard
(22)) suggest that the third parameter which influences the ultraviolet excess,
and in particular also the indices m and m_1, is a chemical-composition para-
meter, namely the relative metal content. With regard to the m - index, this
conclusion is confirmed through a theoretical analysis by B. Baschek (23).
O. Eggen and A. Sandage (24) have investigated the question of the ultraviolet
excess. According to this interpretation the late F and early G stars with
relatively large Δm_1 would correspond to the weak-line stars of Nancy G. Roman
(25), those with relative small Δm_1 to the strong-line stars.

G. Wallerstein and M. Carlson (26), and G. Wallerstein (27) have
determined relative chemical abundances for a number of metals for main sequence
stars around spectral class G0. The results were derived from quantitative
analysis based on high-dispersion spectra. These authors found a very good
correlation between ultraviolet excess and relative metal content, in particular
the Fe/H ratio.

Using the m_1-indices of the photoelectric uvby photometry we arrive at
a similar result. A standard relation between b-y and m_1, valid for stars near
the zero-age line and with the chemical composition of Hyades stars, was derived
for b-y $0^m.22-0^m.40$ from the photometry of members of the Hyades cluster. It
was found to be very close to the lower-envelope relation between m_1 and b-y
found from the distribution in the m_1-(b-y) diagram as shown in Fig. 2 (allow-
ing for the known photometric scatter). An analysis in which the m_1-(b-y)
relation was examined for groups of stars separated according to Δc_1 suggested
no systematic change of the relation with Δc_1 (i.e. with absolute magnitude)
within the main sequence band ($\Delta c_1 < 0^m.15$). We now define a metal-index
deviation Δm_1 as $\Delta m_1 = m_1$ (standard relation)$-m_1$. According to this definition
a positive Δm_1 means a relative metal content below the Hyades standard value.

Fig. 3 shows the relation between Δm_1 and the quantity $\left[Fe/H\right]$, defined
by Wallerstein as

$$\left[\frac{Fe}{H}\right] = \log \left(\frac{\text{Abundance of Fe}}{\text{Abundance of H}}\right)_{star} - \log \left(\frac{\text{Abundance of Fe}}{\text{Abundance of H}}\right)_{sun}$$

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for the stars observed in both programs. Two extreme population II subdwarfs fainter than apparent visual magnitude $6^m_.5$ have been included. This type of star, with Δm_1-values $0^m_.15$-$0^m_.20$ is not respresented in the sample of stars brighter than $V \approx 6^m_.5$.

The material, although not very extensive, suggests a linear relation between $[Fe/H]$ and Δm_1. The scatter is about as expected in view of the probable errors in the determinations of $[Fe/H]$ and Δm_1. It appears that $[Fe/H]$ can be predicted from Δm_1 with a p.e. of about $\pm$ 0.1.

Having considered the late F and early G stars we regard the early F stars in the b-y range $0^m_.22$ - $0^m_.25$. Here the scatter in the m_1-(b-y) diagram is relatively small. The r.m.s. deviation of Δm_1 from the average value is $\pm$ $0^m_.010$, or $\pm$ $0^m_.007$ after correction according to the known p.e. of the m_1-values. If the p.e. of the photometry is underestimated, then the real range of variation is of course correspondingly smaller, and an increase of the p.e. by about one-third would suffice to account for the entire scatter for the early F stars under consideration. The derived actual scatter must therefore be regarded as an upper limit.

In the b-y range considered the index m_1 is less sensitive to changes in the metal content than in the b-y range of the calibration stars of spectral type around G0, by a factor estimated to be about 2. However, this does not fully explain the reduced scatter in m_1; the group of stars must also be more homogeneous with regard to chemical composition. This is a plausible result since we are dealing with stars for which the average age and the age range are much smaller than for the group of late F and early G stars. From the m_1-data the r.m.s. deviation of $[Fe/H]$ from the mean value is estimated to be only $\pm$0.15 (upper limit) for the early F stars in question.

As we go to still earlier stars on the main sequence we might perhaps expect the scatter in the m_1-(b-y) diagram to become still smaller, since the sensitivity of m_1 to chemical composition changes becomes smaller, as does the average stellar age. What we see in Fig. 2 is, however, a big increase in the scatter as we pass b-y $\approx 0^m_.21$, corresponding to spectral class F1. Clearly, for a color range b-y beginning at $0^m_.21$ and extending at least to $0^m_.05$ (spectral class A2) the spectral properties are significantly influenced by a third parameter, beyond the basic mass and age parameters, which here cannot be identified with any quantity characterizing the initial chemical composition.

In Fig. 2 metallic line stars are denoted by triangles, and it is seen

that most of these stars are found in the lower part of the range of variation of m_1, i.e. they tend to have high m_1-values. Quite a few stars with high m_1-values are not in the present lists of known metallic line stars. It would be of interest to examine classification spectra of the stars in question to see what fraction might be metallic line stars according to the standard definition.

D. Chalonge and collaborators (4) have spectrophotometrically compared the intensity distribution in the continuous spectrum of metallic line stars with that of normal stars in the wavelength range 4000 - 6000Å and found pronounced differences. The differences correspond to those in the m_1-indices just discussed. However, since it is not quite clear to what extent the spectrophotometry in question is influenced by absorption lines a detailed comparison with the uvby photometry results cannot be made. It appears that spectrophotometry carried out with high dispersion is necessary in order to separate possibly existing true continuum effects and absorption line effects, and such measures are not yet available.

For the color index range b-y $0.^m0$ to $0.^m2$ the influence of the absorption line $H\beta$ on the v-band intensity, though small, is quite noticable. This produces an absolute magnitude dependence of the index m_1. A small correction equal to $+ 0.1 \Delta c_1$ was applied to the m_1- values in this color range in order to eliminate the effect. The m_1-values plotted in Fig. 2 were corrected in this way. It may be noted that the $H\beta$-effect slightly increases the sensitivity of the index c_1 to absolute magnitude and therefore improves the scale of the c_1-(b-y) method for determining M_v.

The problems of metallic line stars. and the broader problems of the nature of the third parameter that influences the properties of A stars and early F stars, appear at the present time to be quite complex. The following discussion deals only with a few of the many relevant questions, and no definite conclusions are reached.

It is known that the value of the rotational velocity parameter v sin i is on the average much lower for metallic line stars than for normal A and F0 stars (cf. A. Slettebak (28)). On the basis of the results obtained by Slettebak for stars brighter than $V=5.^m0$ we have investigated the correlation of m_1 with v sin i. There is a pronounced tendency for the values of v sin i to become smaller as one goes to stars with larger m_1-values. This could mean that stars with large m_1, and in particular the metallic line stars are seen pole-on, but in view of the results obtained by H. Abt (29) on the occurrence and properties of spectroscopic binary systems among metallic line stars

this interpretation does not appear very plausible. If on the other hand there is a strong correlation between m_1 and v, then one would expect that all stars with large $v \sin i$, and therefore with large v, would have small m_1, and furthermore that all stars with large m_1 would have small v, and therefore small $v \sin i$. Fig. 4 illustrates the point. Although the available material of $v \sin i$-values is small the complete agreement with expectation appears to be of significance.

As one goes along the main sequence toward early types i.e. toward larger mass, the third-parameter phenomenon under discussion sets in rather suddenly at spectral class F1. A change in mass of, say, 10 per cent brings about a complete change. We therefore ask the question. What property, or properties, of the structure of main sequence stars varies rapidly with mass, for masses around 1.5 solar masses.

It was shown by Struve that the average rotational velocity of main sequence A, F and G stars decreases with increasing color index, and that this decrease is very rapid near the transition point at F1 that we are considering here.

With regard to internal constitution of main sequence stars, it is well known that there is, somewhere between G0 and A0, a transition from a structure with a relatively deep outer convection zone to one in which convective instability in the outer part of the star is limited to quite a shallow layer near the surface. According to N. Baker (30) the mixing-length theory of turbulent convection predicts that the transition occurs near $T_e = 7400°$, or spectral type F1 (if it is assumed that the ratio of mixing-length and scale-height is 2). It is also known that as one goes to larger masses a convective core first occurs at about 1.5 solar masses, or near F1, and remains a feature of the structure through the range of O, B and A type main sequence stars.

The relevance in the present context of either of these transition phenomena may be further explored. I should like to comment on the possible role of the changes in the properties of the outer convection zone. If, as has been suggested, contamination of the atmosphere as a consequence of circumstellar nuclear processes is essential to produce a metallic line star, then a necessary condition for the phenomenon to occur would appear to be the absence of appreciable mixing of the stellar atmosphere with deeper layers. A deep convection zone would practically prevent contamination. Rapid rotation might also lead to sufficient mixing of the atmosphere with deeper layers for the contamination effect to be strongly reduced. In this connection it should be noted that N. Baker and R. Kippenhahn (31) have shown that the velocity of circulation in meridional planes caused by rotation is inversely

proportional to the local density and therefore relatively high in the outer layers. The circulation velocity being proportional to the square of the velocity of rotation v the degree of mixing varies strongly over the relevant range of v. This suggests that it would be useful to examine the following picture: A deep outer convection zone produces mixing that prevents contamination of the atmosphere. At the effective temperature where this type of mixing ceases the third-parameter phenomenon sets in. Rapid rotation produces mixing that strongly reduces contamination, and the rapid rotators therefore form a sequence in the m_1-(b-y) diagram that is nearly continuous with the sequence of convective stars (cf. Fig. 4). In the slow rotators contamination plays a role, and in the m_1-(b-y) diagram these stars fall below the sequence of convective stars and rapid rotators. Further analysis may well prove the picture to be incorrect. In particular, it might be found that circumstellar nuclear processes are ineffective against the mixing in even slow rotators, or that effects of anomalous abundances, and the effects of different pressure-density relations in convective and radiative atmospheres (cf. Rudkjøbing (32)) do not suffice to explain the spectroscopic anomalies of metallic line stars. However, if it were found to be valid the analysis of the m_1-(b-y) diagram would yield a valuable observational determination of the effective temperature at which deep convection sets in on the main sequence.

We now return to the question of the possible influence of the chemical-composition parameter on the absolute magnitudes M_v determined from b-y and c_1. We shall consider first the late F and early G stars. Both the u-band and the v-band intensities are sensitive to relative metal content, but in the color difference c_1 there is at least a partial compensation of the effects. An M_v-calibration on the basis of cluster parallaxes and trigonometrical parallaxes was carried out separately for stars with small and large Δm_1- values. In this way it was determined that a correction of the c_1-values equal to +0.75 Δm_1 is required for the calibration of the c_1-(b-y) diagram corresponding to $\Delta m_1 = 0$ (Hyades composition) to be valid. The factor 0.75 applies to the color range b-y $0^m.25$ - $0^m.40$. It may vary with b-y within this range but the calibration material indicates that such variation is small.

The m_1-corrections to M_v average only a few tenths of a magnitude, but they may amount to about 1^m, and the extension from a two-dimensional to a three-dimensional classification scheme is therefore important for accurate determinations of M_v. In this connection reference is made to the spectrophotometric three-dimensional classification scheme of D. Chalonge (4).

For the color range b-y $0^m.00$ - $0^m.20$ the m_1-effect was investigated using M_v-values for metallic line stars in the Hyades and Coma clusters. We have already seen that the effect is small here. A correction of the c_1- values by

-0.15 Δm_1 is indicated, where Δm_1 is counted from a standard line defined by the normal Hyades cluster stars.

We turn next to the question of the determination of stellar ages from the indices obtained through the photoelectric uvby photometry. In principle a direct calibration of the c_1-(b-y) diagram in terms of mass and age is possible on the basis of theoretical calculations of stellar evolution combined with model atmosphere calculations. We shall, however, limit ourselves here to a discussion of efforts aiming at mass and age calibration of the Hertzsprung-Russell diagram. In other words, we translate location in the c_1-(b-y) diagram into location in the Hertzsprung-Russell diagram using the observationally determined M_v-calibration that we have just discussed, and then utilize computed tracks of evolution in the Hertzsprung-Russell diagram to find the mass and the age.

In the following discussion we shall consider mainly the problems of the younger main sequence stars, i.e. B, A and early F stars, returning however to certain questions regarding the late F and early G stars.

The theoretical work on stellar evolution through the hydrogen burning phase, referred to in the introduction, has yielded mass-age calibration of the desired type for the spectral range in question (cf. e.g. L. Henyey, R. LeLevier and R. Levee (33)). For our ultimate purpose of combining stellar ages and space velocities to give the places of formation in the galaxy we need ages of relatively high accuracy. An improved age calibration appeared desirable.

The following results on evolution through the main sequence band for stars in the mass range 1.5-4 solar masses were obtained in collaboration with Mr. T. Kelsall, Goddard Space Flight Center, Greenbelt, Md.

Improved stellar opacity tables, computed with the aid of an IBM 7090 computer and a code developed at the Los Alamos Laboratories (cf. A. Cox (34)) were used. The expression for the energy generation was chosen according to recent revisions of relevant cross-sections (cf. W. A. Fowler (35) and H. Reeves (36)). Further improvement of the basic data will soon be possible, in particular with respect to the opacities. A. Arking and J. Herring (37) have made detailed calculations of the effect of absorption lines on stellar opacities, and when corresponding opacity tables are available, the stellar model calculations will be repeated. However, in the mass range considered the resulting changes should be fairly small.

As in previous work of this kind a chemical composition representative

of the young population I stars in question must be determined (cf. the investigations already referred to, also D. Morton (38) and I. Iben and J. Ehrman (39)). Calculations were made for four different compositions (X,Y,Z), and a composition was determined by the conditions that the observational zero-age line must be reproduced, and that the correct luminosity must result for a star on the zero-age line of mass equal to that Sirius A (Sirius A is so close to the zero-age line that the projection back on this line can be effected without much uncertainty). It was found that these conditions are nearly satisfied for $X = 0.70$, $Y = 0.27$ and $Z = 0.03$.

For a given mass M and chemical composition the stellar model calculations give the radius R and the luminosity L as functions of time. The effective temperature T_e follows, of course, but for the determination of the track of evolution in the Hertzsprung-Russell diagram knowledge of bolometric corrections, and the temperature scale connecting T_e and the color index used, is necessary. For the spectral range in question the variations of the bolometric correction with absolute magnitude, for given color index, within the main sequence band are small, and we shall neglect them for the present. Therefore, if location in the Hertzsprung-Russell diagram is expressed in terms of color index and vertical separation $\triangle M_v$ from the zero-age line, the bolometric correction is eliminated.

With regard to the temperature scale for the late B and A stars there is still some uncertainty. In a recent discussion by D. Popper (40) this is estimated to be $\pm 500^{\circ}$ at A0, corresponding to about $\pm 0^{m}.03$ on the b-y color index scale. This uncertainty contributes noticably to the uncertainty of the age calibration. The method of combining the results of model atmosphere calculations giving intensities in the continuous spectrum as a function of effective temperature T_e and gravity g with observed intensity ratios for suitably chosen wavelengths has been used to determine effective temperatures. However, although the relative photometry (comparing different stars) is of quite high accuracy, the possible errors of the absolute photometry are still a limiting factor of the method.

The photoelectric uvby photometry has been used to obtain a check on the temperature scale through a procedure that does not require the use of absolute photometry. From model atmospheres computed by K. Osawa (41) the color index difference c_1 was calculated as a function of effective temperature on the zero-age line. Comparison with the observational c_1-value at the maximum near A0 determined the value of the constant (arbitrary in relative color

index phototometry) which must be added to the observed c_1-values. These then gave zero-age line effective temperatures as a function of b-y for late A stars where c_1 varies strongly with b-y (and where the absorption line corrections are not yet appreciable). From these effective temperatures the constant to be added to the observed color indices b-y for comparison with the model atmosphere values could be evaluated, and the temperature scale T_e (b-y, c_1) derived. The T_e-values found in this way are a little higher than those of the Popper temperature scale, but agree with the latter within the estimated errors.

The following table gives as an example the results of Mr. Kelsall's computation of the evolutionary track for X = 0.70, Y = 0.27, Z = 0.03, for log $M/M_\odot$ = 0.45, through the hydrogen burning phase. For a series of models the table gives the age, the hydrogen content X_c at the center, M_{bol}, R, T_e, ΔM_{bol}, the relative mass of the core, the relative energy production in the core, T_c and $\mathcal{S}_c$.

Age Billion years	X_c	M_{bol}	$\frac{R}{R_\odot}$	T_e	M_{bol} from zero-age line	Core rel.mass	Core rel. energy pr.	T_c million degrees	$\mathcal{S}_c$
0.000	0.70	$0\overset{m}{.}0$	1.88	12100°	$0\overset{m}{.}0$	0.17	0.94	23.0	40
0.011	0.69	0.0	1.90	12100	0.0	0.17	0.94	23.1	40
0.100	0.55	-0.1	2.09	11800	0.3	0.14	0.94	23.7	42
0.163	0.42	-0.1	2.29	11400	0.5	0.12	0.94	24.4	44
0.213	0.29	-0.2	2.53	11000	0.8	0.10	0.94	25.2	48
0.252	0.16	-0.2	2.81	10500	1.1	0.07	0.94	26.3	55
0.266	0.10	-0.2	2.93	10300	1.2	0.07	0.94	27.1	61
0.268	0.08	-0.2	2.95	10300	1.2	0.06	0.95	27.3	62
0.270	0.07	-0.2	2.96	10300	1.3	0.06	0.95	27.5	64
0.273	0.06	-0.3	2.98	10300	1.3	0.06	0.95	27.8	66
0.277	0.04	-0.3	2.99	10300	1.3	0.06	0.95	28.3	70

We see from the M_{bol} column that the computed width of the band corresponding to hydrogen burning is approximately $1\overset{m}{.}4$ at an effective temperature $T_e = 10300^o$, i.e. close to A0.

Comparing the computed evolutionary track with those obtained in similar calculations by Kushwaha (42), Henyey, Le Levier and Levee (33), and Hoyle and Haselgrove (43), we see that it does not differ greatly, in spite of fairly

great difference in the assumptions regarding chemical composition, opacity and energy generation.

In the table below are given values of age, $\log T_e$ and M_{bol} as a function of X_c for the following masses: $\log M/M_\odot = 0.45, 0.40, 0.35,$ and 0.30. The computations were made by Mr. T. Kelsall.

X_c	Age billion years	$\log T_e$	M_{bol}		X_c	Age billion years	$\log T_e$	M_{bol}
0.70	0.00	3.97	$0^m.0$		0.70	0.00	4.01	$0^m.0$
0.60	0.16	3.97	0.1		0.60	0.12	4.00	0.1
0.50	0.30	3.96	0.3		0.50	0.12	4.00	0.3
0.40	0.42	3.95	0.4		0.40	0.31	3.99	0.5
0.30	0.52	3.94	0.5		0.30	0.38	3.98	0.7
0.20	0.60	3.93	0.7		0.20	0.44	3.96	0.8
0.10	0.67	3.92	0.8		0.10	0.49	3.95	1.0
0.05	0.70	3.92	0.9		0.05	0.51	3.95	1.1

$$\log \frac{M}{M_\odot} = 0.30 \qquad\qquad \log \frac{M}{M_\odot} = 0.35$$

X_c	Age billion years	$\log T_e$	M_{bol}		X_c	Age billion years	$\log T_e$	M_{bol}
0.70	0.00	4.05	$0^m.0$		0.70	0.00	4.08	$0^m.0$
0.60	0.09	4.04	0.2		0.60	0.07	4.08	0.2
0.50	0.16	4.03	0.3		0.50	0.12	4.07	0.4
0.40	0.23	4.02	0.5		0.40	0.17	4.06	0.6
0.30	0.28	4.01	0.7		0.30	0.21	4.04	0.8
0.20	0.32	4.00	0.9		0.20	0.24	4.03	1.0
0.10	0.36	3.98	1.1		0.10	0.26	4.01	1.2
0.05	0.37	3.98	1.2		0.05	0.27	4.01	1.3

$$\log \frac{M}{M_\odot} = 0.40 \qquad\qquad \log \frac{M}{M_\odot} = 0.45$$

We shall now consider the second of the questions raised in the introduction. We note that the computed zero-age line agrees very well with the observed line through the spectral range under consideration. This is satisfactory, however it is clear that we do not here have a very sharp test of the theory, since one chemical composition parameter was chosen to bring about agreement near A0, and because there is still some uncertainty about the temperature scale. Next we come to the question of whether or not the observed width of the main sequence band can be accounted for on the basis of the computed tracks of evolution during the hydrogen burning phase. The computed width is about $1^m.3$ at b-y $= 0^m.05$ and $1^m.0$ at b-y $= 0^m.15$. Comparison with the observed distribution in the

Hertzsprung-Russell diagram of stars that are members of galactic clusters might give the impression that the computed width is somewhat too small, however the well known widening effect by undetected spectroscopic binaries must be kept in mind in this connection. Here we shall discuss in some detail the comparison with the observed distribution in the c_1-(b-y) diagram (cf. Fig. 1).

Consider the color range $0^m.07$ - $0^m.13$ where the average computed main sequence width is $1^m.1$. From the observed distribution in the c_1-(b-y) diagram we find (allowing for observational scatter) that about 15 per cent of the 200 stars in question are above the computed main sequence band region, and within $0^m.6$ of its upper limit. Now we must allow for the fact that we are dealing with a sample of stars brighter than apparent magnitude V = $6^m.5$ so that the stars above the main sequence band populate a larger volume. When correction is made for this effect it appears that only about 5 per cent of the stars are in the considered band above the computed main sequence region. A good fraction of these stars may be stars that have exhausted the supply of hydrogen in the central regions and are evolving away from the main sequence region. The remaining effect of scatter beyond the computed main sequence band is therefore small. Relatively minor revisions of the results of theoretical calculation might reduce it significantly.

Again allowing for the volume effect we find that the fraction of stars that are located more than $0^m.6$ above the computed upper limit of the main sequence is quite small. A few of these luminous stars are appreciably reddened and should not be included in the statistics. It appears unlikely that interpretation of the remaining stars in terms of evolution beyond the main sequence stage should present any difficulty.

Altogether the predictions based on the theoretical calculations appear to agree rather well with the observations, for the color range under consideration. A small remaining difference between the predicted and the observed width of the main sequence band may be due mainly to the influence of the rotational-velocity parameter.

If we go beyond the spectral range of the A stars to later types, we find that the computed width of the main sequence band becomes considerably smaller. Mr. Kelsall's calculations for $\log \frac{M}{M_\odot} = 0.20$ confirm a result previously found by Hoyle (43) that the evolutionary changes of luminosity and effective temperature with age are very small here during most of the hydrogen burning phase. It is also known that the tracks of evolution of stars of approximately solar mass differ in character from those of the A stars, with both the effective temperature

and the luminosity increasing during the early part of the hydrogen burning phase (cf. e.g. R. Sears (44)). Further work on the intermediate mass range, in which the outer convection zone is taken into account as well as is possible, appears desirable. We shall limit the present discussion as far as it is based on stellar evolution calculations to $b-y \leq 0\overset{m}{.}16$, i.e. to the spectral range of the A stars.

For the main sequence A stars ages determined from location in the $c_1-(b-y)$ diagram using the absolute magnitude calibration and the computed tracks of evolution would appear to merit sufficient confidence for consideration in connection with the observed space velocities according to the program outlined in the introduction. We may note that the calibration curves indicate that for the upper half of the A star main sequence band the age is essentially a function of the color index b-y, and that here an age difference of 100 million years corresponds on the average to a difference of $0\overset{m}{.}04$ in b-y.

Future extension of the work to unreddened A0 stars appears quite feasible with the combination of uvby photometry and Hβ photometry. If a further extension to reddened A0 stars should be desirable, then the addition of another index, such as a K-line index, would be required.

It should be emphasized that there are in the spectral range of the A stars peculiar stars for which the scheme of age determination fails. H. W. Babcock (45) on the basis of his measures of the Zeeman has given a catalogue of 89 stars showing evidence of magnetic fields. Most of these stars are too early in spectral type, or too faint, to be in the catalogue of photoelectric uvby photometry, but there are 13 stars in common. Of these 4 are outside the spectral range we are discussing (negative color index). Of the remaining 9 stars 5 have relatively small magnetic fields ($H_e < 500$ Gauss), and these stars appear normal from the point of view of their photometric indices. For 3 of the small-field stars (68 Tau, 16 Ori, ∮ Vir) the photometric M_v corresponding to the indices could be tested, and the residuals were found to be less than $0\overset{m}{.}2$. However, the age determined for 68 Tau from the location in the Hertzsprung-Russell diagram is lower than the expected Hyades cluster age by several times the estimated probable error.

Four of the stars considered have relatively large magnetic fields. Data for the comparison of the magnetic and photometric properties are given on the next page.

Babcock No.		b-y	m_1	Δc_1	Extremes of effective field in Gauss according to Babcock	
28	53 Cam	$0\overset{m}{.}057$	$0\overset{m}{.}254$	$-0\overset{m}{.}196$	-5120	+3700
37	HR 4369	0.107	0.254	-0.034	-1000	+800
55	β Cr B	0.140	0.255	-0.058	-960	+1020
78	γ Equ	0.147	0.242	-0.028	+180	+880

The stars stand out through their high m_1-values (cf. Fig. 2) and negative Δc_1-values. The case of 53 Cam (not plotted in Fig. 1) is particularly striking. The age determination scheme clearly fails here.

The peculiar stars in question constitute a small fraction of the stars in the spectral range in question, and their inclusion would affect statistical results to a small degree only. In a sample of bright stars the peculiar stars are, of course, known and can be excluded. In fainter samples the stars with high m_1-values might be excluded for a test of the influence of peculiar stars.

We turn now to a discussion of the third of the questions formulated in the introduction. In principle the determination of the place of formation of a star from its age and space velocity is, for course, a relatively simple problem. The question is whether or not the ages and space velocities are accurate enough, and the gravitational field of the galaxy known well enough, for the results to contribute significant information, valid for individual stars or statistically. Our discussion has described the attempts at increasing the accuracy of the determinations of age and space velocities. I should like now to summarize briefly some of the results obtained in the applications.

We shall subdivide the stars into age groups and consider the distribution of the stars in velocity space for each age group. This type of approach has been adopted in a large number of investigations starting with the discussions of the relation between radial velocity and spectral class. Reference is made in particular to recent investigations by J. Delhaye (46), P. Parenago (47), A. N Vyssotsky (48), A. Blaauw (49), R. v. d. R. Woolley (50), R. v. d. R. Woolley and O. Eggen (51), and O. Eggen (52) and (53).

Fig. 5 shows the distribution of the stars of six age groups in the UV-plane (U is the velocity component, corrected for solar motion, in the direction of the galactic center, V in the direction $l=90°$, $b=0°$). The stars in the age group 0÷20 million consist of B8-9 stars in D. Crawford's photometric catalogue which according to their location in the $\beta-(U-B)_o$ diagram have ages in this range. The groups 200-300, 300-400 and 400-600 million years contain the

stars in the photometric uvby catalogue in the color range b-y $0^m_.05$ - $0^m_.16$ which according to their location in the c_1-(b-y) diagram belong to the respective groups. The 600-900 million year group was similarly selected, but only stars from the upper half of the main sequence band were included since the ages are not sufficiently well determined near the zero-age line for the color index range in question.

The age group 0-20 million years shows the expected nearly circular distribution with relatively small dispersion. For the age group 200-300 million years we note the appearance of a feature at the upper right-hand side of the distribution which is also brought out by the work of Delhaye and Blaauw referred to above, although not so clearly. It can be approximately described as a ridge extending to the left from the point corresponding to the motion of the nucleus of the Ursa Major stream. An addition also appears at the lower left corner of the distribution, near the point corresponding to the motion of the Hyades stream. The additions produce the well known ellipsoidal, vertex-suifted distribution characteristic of the A stars. There is a striking absence of stars in the lower right-hand quadrant of the UV-plane.

For the age group 300-400 million years the Ursa Major feature in the velocity distribution has disappeared while the Hyades feature has been strenthened. The lower right-hand quadrant is still nearly empty.

Inspecting the velocity distribution for the age group 400-600 million years we see that the Ursa Major feature has reappeared in approximately the same area, and that the region around the Hyades point is still populated while there are hardly any stars in the quadrant mentioned.

The age group 600-900 million years in the present material contains rather few stars. However, the results suggest that further investigations based on an extended and improved age calibration for the upper half of the main sequence band in the spectral range of late A stars and F stars should give the answers to a number of questions regarding the transition to the relatively smooth ellipsoidal velocity distribution characteristic of groups of greater age.

Comparison of the velocity distribution for the combined age groups 200-300 million years and 400-600 million years with that for the group 300-400 million years shows a pronounced difference in the population of the general area of the Ursa Major feature.

The next step in the discussion is the analysis of the distribution of the places of formation of the stars computed on the basis of the space velocities and ages. In today's lecture I should like to limit discussion to the

kinematics of the main sequence stars, so I shall make only brief comments of a
general nature regarding the broader problem.

If the velocity components are known with an accuracy of about $\pm$ 2 km/sec and
the ages to $\pm$ 10 to 15 per cent of the main sequence lifetime, then the computed
places of formation should give significant information regarding formation in
associations for groups of stars with lifetimes up to about 100 million years.
For groups with lifetimes up to about 1000 million years the discussion should
yield information on spiral arm structure, more particularly on sectors of
spiral arms that are active in star formation. The information is less precise
than in the previous case but pertains to a larger volume of the galaxy. For
stars much older than 1000 million years only conclusions concerning the overall
structure of the galaxy can be drawn (the uncertainty in the age being of the
same order as or larger than the characteristic periods of the galactic motion),
unless special circumstances make it possible to select relatively small portions
of the galactic orbit where star formation is most likely to have taken place
(cf. e.g. the discussion of disc high-velocity stars by U. Van Wijk (54)).

The pronounced clumpiness in the velocity distribution, and the marked
changes with the age range of group considered (cf. Fig. 5) show that star
formation did not occur with approximately equal, or smoothly varying probability
over the relevant galactic regions. We conclude that the observational material
of space velocities and ages does contain information regarding star formation in
spiral arms.

To each point in the UV-plane there corresponds a galactic orbit, and according
to the relevant age range a certain portion of this orbit is indicated as the
center of a region of probable star formation. We can thus translate the data
contained in diagrams such as those presented in Fig. 5 into information on
star formation, provided we have available sufficiently detailed tables describing
galactic motion as a function of time and the parameters U and V. For a given
gravitational field the computation of such tables with the help of electronic
computers is, of course, a relatively simple matter (the volume occupied by
the star samples considered, although relatively small, is not negligibly small, but
it presents no difficulties to allow for this).

As an example consider the entity of galactic orbits corresponding to U and V
values of the lower right-hand quadrant. If on all these orbits we mark the
portions corresponding to the age range 100-600 million years (cf. Fig. 5), then
we delineate regions of the galaxy where the probability of star formation was

very low during the time interval in question. On the other hand, a similar construction for the section of the UV-plane where we find what we have referred to as the Ursa Major feature would outline a galactic region of high probability of star formation.

B. Lindblad (55) has examined the phenomenon of the vertex deviation found for the A stars in terms of dispersion orbits, defined as the orbits along which an association of stars tends to disperse in the central field of the galaxy. Lindblad suggested that the stars of young population I which are responsible for the vertex deviation may have originated in one vast cloud; following Oort we might say, perhaps part of a spiral arm.

I. King (56) has pointed out the importance of this context of the epicycle period given by $\pi/\sqrt{-B(A-B)}$, where A and B are the Oort constants. With the values of A and B given by M. Schmidt (57) this period is 230 million years. It is interesting to pursue this idea in connection with the interpretation of the diagrams of Fig. 5, however it should be emphasized that both the presently used age calibration and the epicycle period are subject to revision that may lead to appreciable changes. The general program which has just been outlined will, of course, when carried out, automatically throw light on the role of the epicycle period.

We shall now return to questions concerning the late F and early G stars. We have seen that for these stars a fairly accurate determination of the relative metal content, in particular of the quantity $[Fe/H]$, is possible on the basis of the indices m_1 and b-y. With the calibration obtained using the results of Wallerstein's quantitative analysis we find that the observed distribution of the late F and early G stars in the m_1-(b-y) diagram corresponds to a range of relative metal content limited by the Hyades value and approximately 0.2 times the Hyades value. As already mentioned the subdwarfs of extreme population II, with relative metal contents around 0.01 times the Hyades value (cf. L. H. Aller and J. L. Greenstein (58)), are so relatively rare that they are not represented in the sample of stars brighter than $V = 6^m.5$.

The wide range of variation of relative metal content for the main sequence stars of the spectral range considered is an important feature, and it is clear that this must be taken fully into account in future work on the calibration of the Hertzsprung-Russell diagram in terms of mass and age. The relative helium content of course also enters the problem, affecting both the location of the zero-age line and the mass-luminosity relation on this line.

Investigations of the relations between age, chemical composition and space velocity for the older stars of the galaxy by a number of astronomers have already led to very important results. With improved age calibration, and data of somewhat increased accuracy for samples of stars complete to given apparent magnitude limits, these investigations could be pushed further. I wish to mention in this connection that an extension of the photoelectric uvby photometry for F5 - G2 stars to the limit $V = 7^{m}.3$ is now under way, and that it will be followed by an extension to $V = 8^{m}.0$ for F8 - G2 stars.

I should like to comment on one result obtained from the present material of Δm_1-values, space velocities, and color indices and absolute magnitudes (for a preliminary, but more general discussion cf. B. Strömgren (59)). The investigations of Greenstein and his associates, of Sandage, O. Wilson, Oke, Wallerstein, and others, have shown that stars of approximately the same chemical composition as the Hyades occur among relatively old stars, older than, say, the galactic cluster M67. Our observational material confirms this result. It shows that the old stars in question have metal contents that average lower than the Hyades value. However, the range of variation is relatively large and does include the latter.

Among the 1217 stars in the catalogue of photoelectric uvby photometry very few have velocity components $|W|$ at right angles to the galactic plane larger than 35 km/sec, and these stars all have metal contents smaller than 0.3 times the Hyades values. This result and the results of extension work by several investigators on the ultraviolet excesses of high-velocity stars suggest that the galactic halo consists almost exclusively of stars with relatively low metal content. The great majority of these stars have metal contents in the range 0.2 - 0.3 times the Hyades value, and only a small fraction are of extreme population II with very low metal content. When the planned extension of the photoelectric uvby photometry to the limit $V = 8^{m}.0$ has been completed it will be possible to carry out a sharper test of this picture.

References

(1) A. Sandage, Le Probleme des Populations Stellaires (Pont. Ac. Sc., Ed. D. J. K. O'Connell), p. 41, 1958.

(2) H. L. Johnson and W. W. Morgan, Ap. J. 117, 313, 1953.

(3) D. Barbier, Principes Fondamentaux de Classification Stellaire, Coll. Int. Centre Nat. Rech. Sc. 55, p. 47.

(4) D. Chalonge, Le Probleme des Populations Stellaires (Pont. Ac. Sc., Ed. D. J. K. O'Connell), p. 345, 1958.

(5) R. M. Petrie, Vistas in Astronomy (Ed. A. Beer), Vol. 2, p. 1346, 1956.

(6) R. F. Griffin and R. O. Redman, M. N. 120, 287, 1960.

(7) T. J. Deeming, M. N. 121, 52, 1960.

(8) T. and J. H. Walraven, B. A. N. 15, 67, 1960.

(9) B. Strömgren, Stars and Stellar Systems, Vol. 3 (Ed. K. Strand), Chapter 9, to be published 1963.

(10) B. Strömgren, Le Probleme des Populations Stellaires (Pont. Ac. Sc. Ed. D. J. K. O'Connell), p. 385, 1958.

(11) B. Strömgren, The Observatory, 78, 137, 1958.

(12) D. L. Crawford, Ap. J. 128, 185, 1958.

(13) D. Chalonge, I. A. U. Symposium No. 10 (The Hertzsprung-Russell diagram, Ed. J. L. Greenstein). Ann. d'Aph. Suppl. No. 8, pp. 61 and 71, 1959.

(14) B. Strömgren, I. A. U. Symposium No. 10 (Hertzsprung-Russell diagram, Ed. J. L. Greenstein, Ann. d'Aph. Suppl. No. 8, 59, 1959.

(15) R. H. Hardie and D. L. Crawford, Ap. J. 133, 843, 1961.

(16) D. L. Crawford, A. J. 66, 281, 1961.

(17) D. L. Crawford, Ap. J., to be published 1963.

(18) H. G. van Bueren, B. A. N. 11, 385, 1952.

(19) H. L. Johnson and C. F. Knuckles, Ap. J. 122, 209, 1955.

(20) B. Strömgren, Le Probleme des Populations Stellaires (Pont. Ac. Sc., Ed. D. J. K. O'Connell), p. 245, 1958.

(21) W. G. Melbourne, Ap. J. 132, 101, 1960.

(22) M. Schwarzschild, L. Searle and R. Howard, Ap. J. 122, 353, 1955.

(23) B. Baschek, Z. f. Aph. 50, 296, 1960.

(24) A. R. Sandage and O. J. Eggen, M. N. 119, 278, 1959.

(25) N. G. Roman, Ap. J. 112, 554, 1950.

(26) G. Wallerstein and M. Carlson, Ap. J. 132, 276, 1960.

(27) G. Wallerstein, Ap. J., Suppl. Series, 6, 407, 1962.

(28) A. Slettebak, Ap. J. 121, 653, 1955.

(29) H. A. Abt, Ap. J., Suppl. Series, 6, 37, 1961.

(30) N. Baker, to be published 1963.

(31) N. Baker and R. Kippenhahn, Z. f. Aph. 48, 140, 1959.

(32) M. Rudkjöbing, Ann. d'Aph. 13, 69, 1950.

(33) L. G. Henyey, R. LeLevier, and R. D. Levee, Ap. J. 129, 2, 1959.

(34) A. Cox, Stars and Stellar Systems, Vol. 8 (Ed. L. H. Aller) Chapter 2,
to be published 1963.

(35) W. A. Fowler, Ninth Int. Astrophysical Symposium, Liege, p. 203, 1959.

(36) H. Reeves, Stars and Stellar Systems, Vol. 9 (Ed. L. H. Aller), Chapter
to be published 1963.

(37) A. Arking and J. Herring, P.A.S.P., to be published 1963.

(38) D. C. Morton, Ap. J. 129, 20, 1959.

(39) I. Iben and J. Ehrman, Ap. J. 135, 770, 1962.

(40) D. M. Popper, Ap. J. 129, 647, 1959.

(41) K. Osawa, Ap. J. 123, 513, 1956. Dr. Osawa has kindly put at my
disposal an unpublished extension of his model atmosphere work to
$T_e = 9600°$.

(42) R. S. Kushwaha, Ap. J. 125, 242, 1957 .

(43) C. B. Haselgrove and F. Hoyle, M. N. 119, 112, 1959;F.Hoyle,M.N. 120, 22, 1960.

(44) R. L. Sears, Ap. J. 129, 489, 1959.

(45) H. W. Babcock, Ap. J., Suppl. Series, 3, 141, 1958: Ap. J. 128,
228, 1958.

(46) J. Delhaye, B. A. N. 10, 409, 1948.

(47) P. P. Parenago, Astr. J. Soviet Union 27, 150, 1950.

(48) A. N. Vyssotsky, P. A. S. P. 69, 109, 1957; also A. J. 56, 62, 1951.

27

(49) A. Blaauw. Le Probleme des Populations Stellaires (Pont. Ac. Sc., Ed. D. J. K. O'Connell), p. 333, 1958.

(50) R. v. d. R. Woolley, M. N. 118, 45, 1958.

(51) R. v. d. R. Woolley and O. J. Eggen, M. N. 118, 57, 1958.

(52) O. J. Eggen, M. N. 118, 560, 1958.

(53) O. J. Eggen, M. N. 120, 448, 1960.

(54) U. Van Wijk, A. J. 61, 277, 1956.

(55) B. Lindblad. Le Probleme des Populations Stellaires (Pont. Ac. Sc., Ed. D. J. K. O'Connell), p. 467, 1958.

(56) I. King, Ap. J. 133, 347, 1961.

(57) M. Schmidt B. A. N. 13, 15, 1956.

(58) L. H. Aller and J. L. Greenstein. Ap. J., Suppl. Series 5, 139, 1960

(59) B. Strömgren, Interstellar Matter in Galaxies (Ed. I. Woltjer), p. 274, 1962.
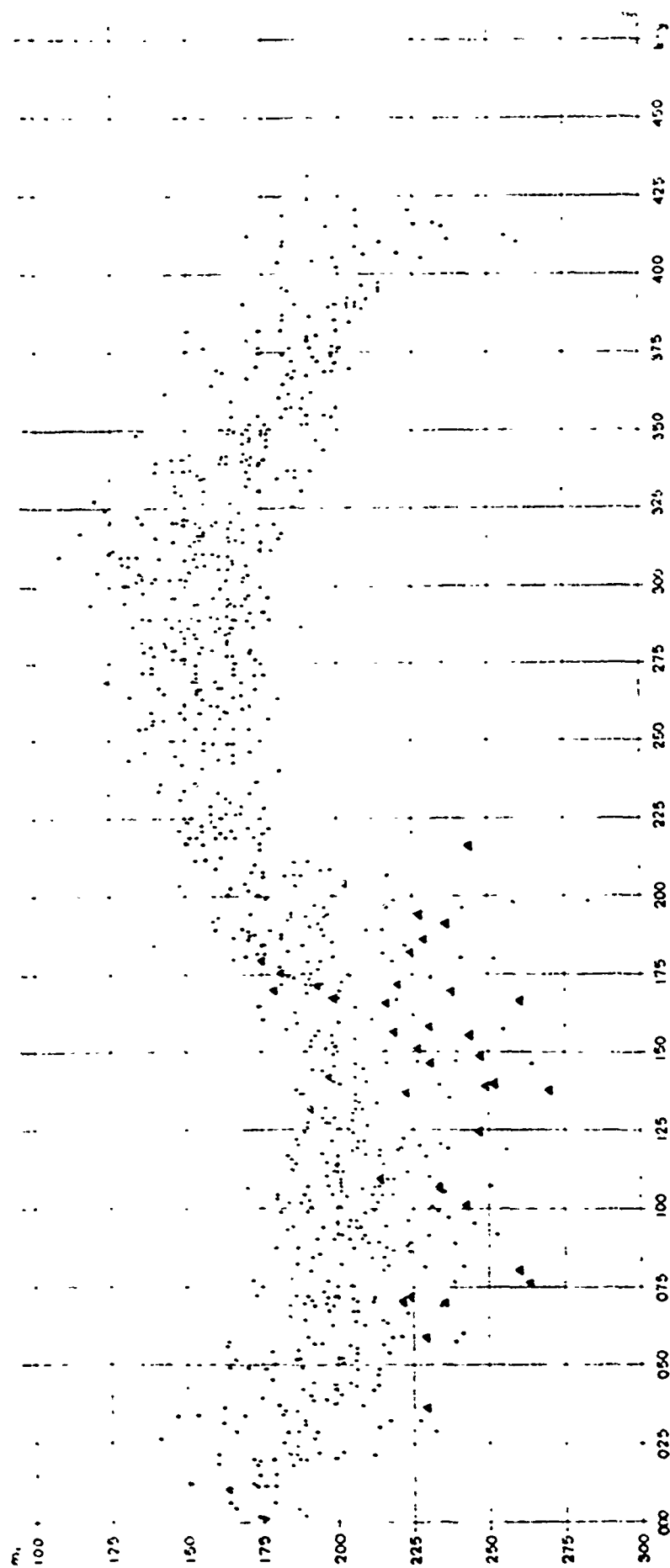
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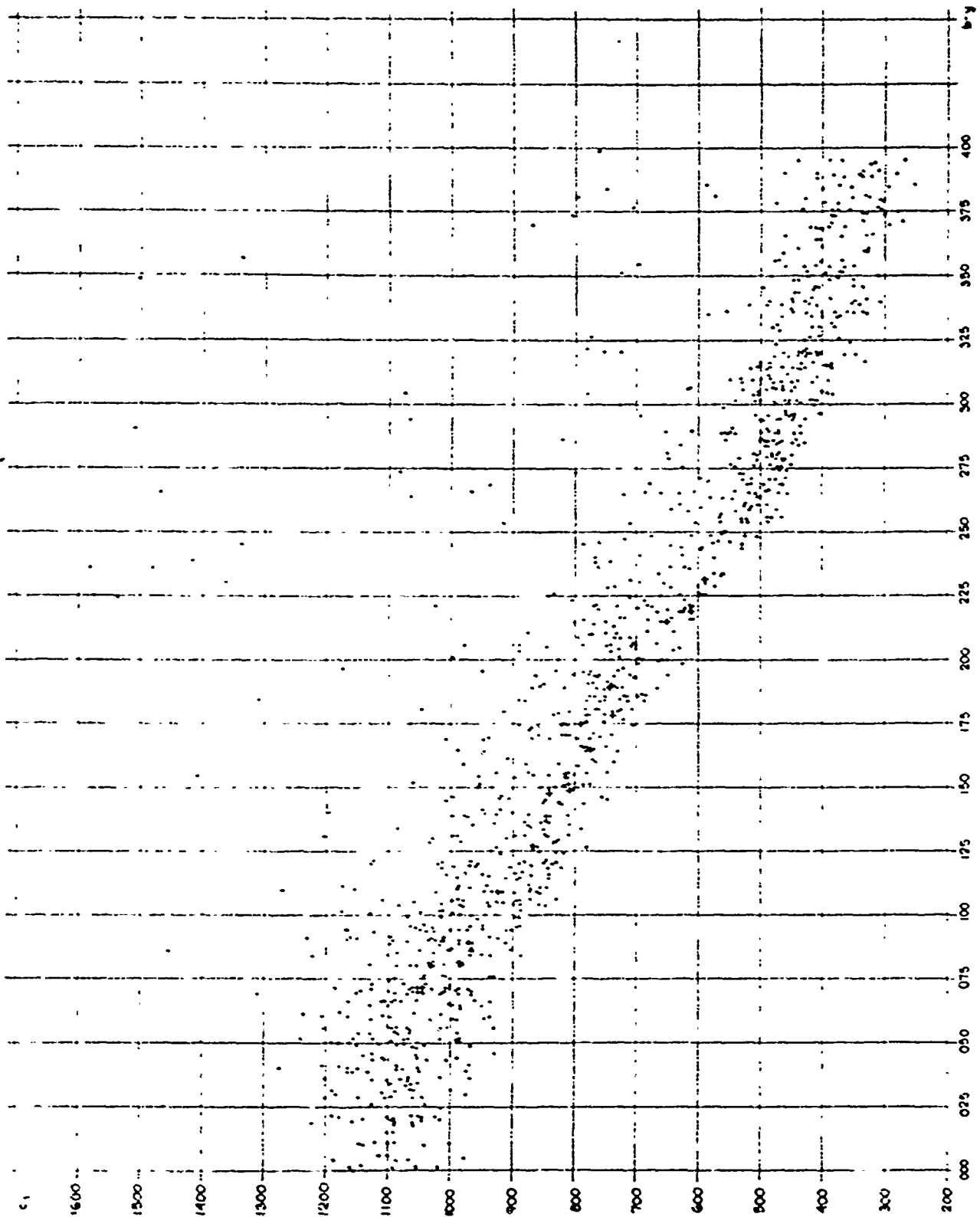
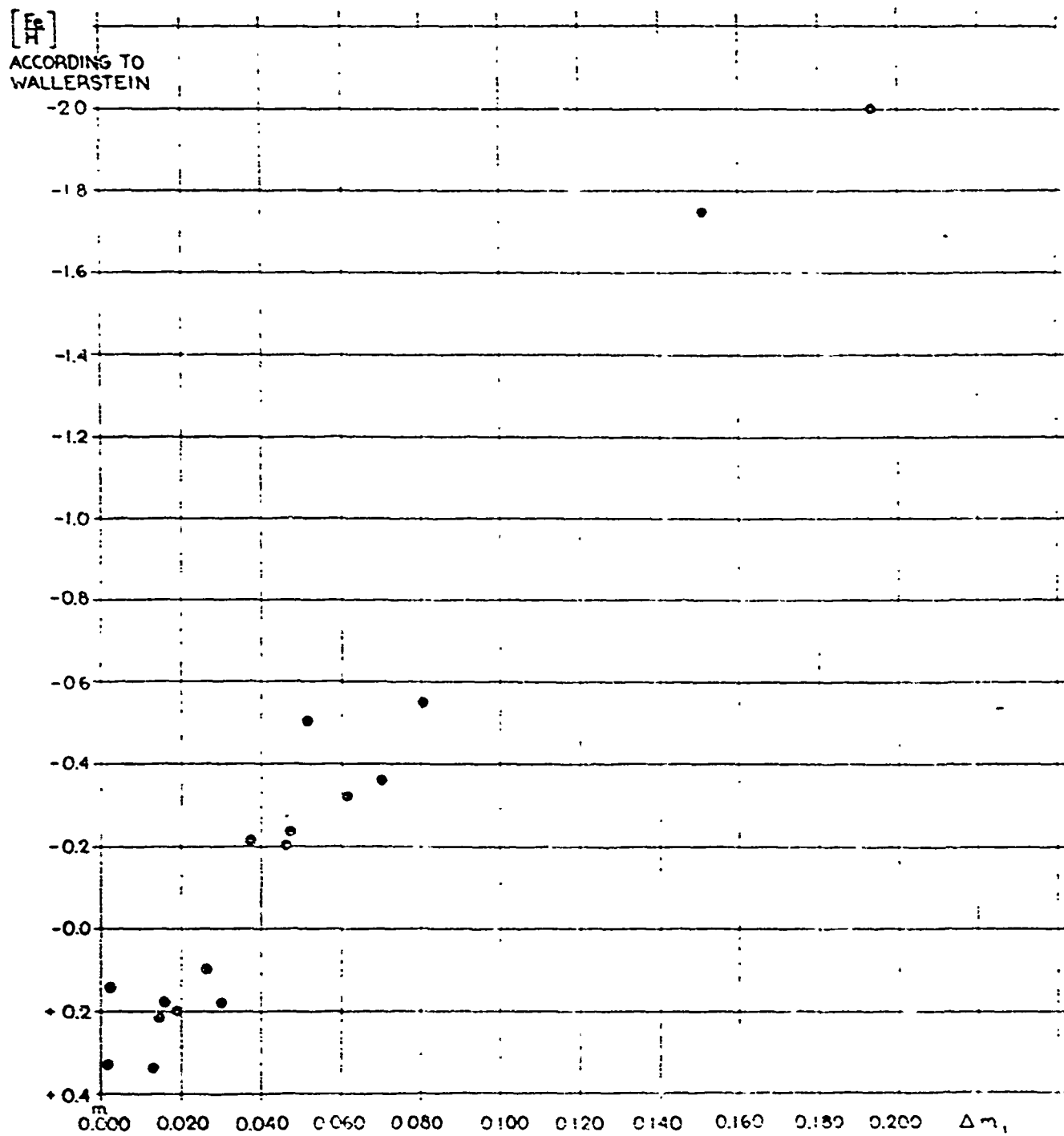Fig. 1. The $c_1 - (b - y)$ diagram.

Fig. 2. The $m_1 - (b - y)$ diagram.

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Fig. 3. The relation between [Fe/H] and Δm₁ for main sequence stars around spectral class G₀.
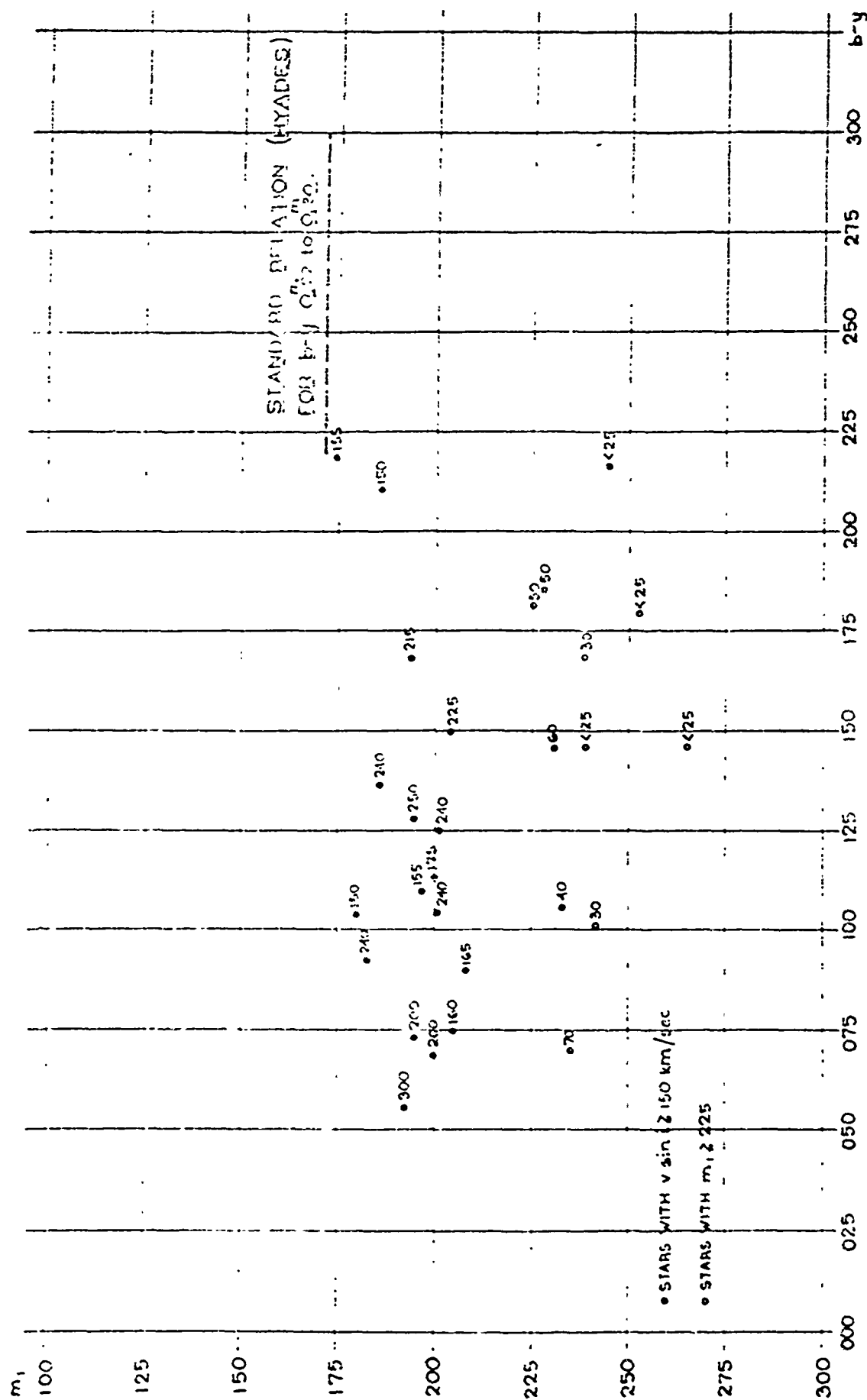
Fig. 4. Correlation of rotational velocity and location in the $m_1 - (b - y)$ diagram.
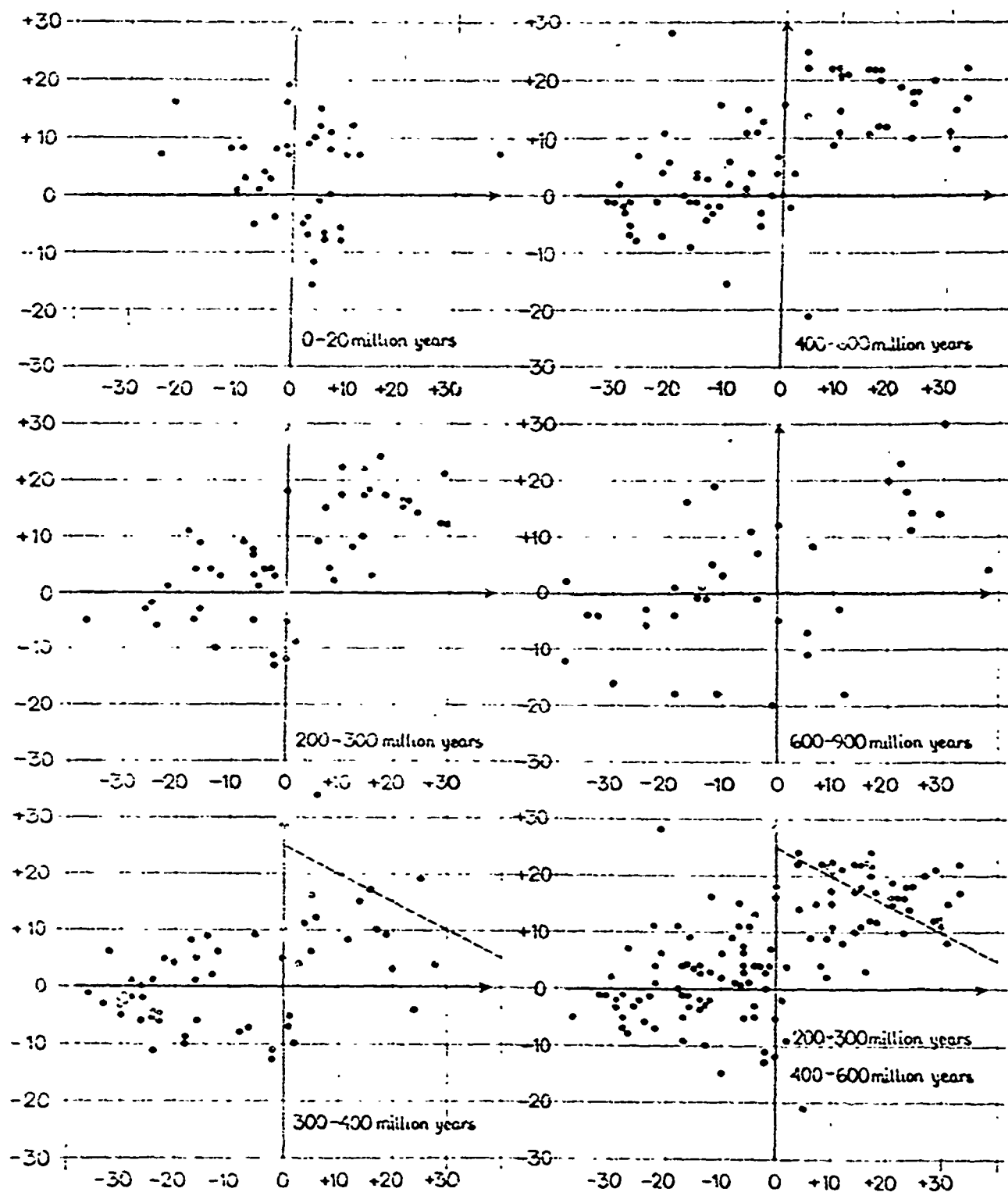
Fig. 5. Distribution of space velocities (projection on the galactic plane) for different age groups.